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**CONTINUOUS DYNAMIC
RECRYSTALLIZATION DURING
FRICTION STIR WELDING OF HIGH
STRENGTH ALUMINUM ALLOYS**

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CONTINUOUS DYNAMIC RECRYSTALLIZATION DURING FRICTION STIR WELDING OF HIGH STRENGTH ALUMINUM ALLOYS

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Introduction

Friction stir welding (FSW) is a solid state joining process [1,2,3] that uses a rapidly-rotating, non-consumable high strength tool-steel pin that extends from a cylindrical shoulder (Figure 1). The workpieces to be joined are firmly clamped to a worktable; the rotating pin is forced with a pre-determined load into them and moved along the desired bond line. Frictional heating is produced from the rubbing of the rotating shoulder with the workpieces, while the rotating pin deforms (i.e., 'stirs') the locally-heated material. To produce a high integrity defect-free weld, process variables (RPM of the shoulder-pin assembly, traverse speed, the downward forging force) and tool pin design must be chosen carefully.

FSW can be considered as a hot-working process in which a large amount of deformation is imparted to the workpiece through the rotating pin and the shoulder. Such deformation gives rise to a weld nugget (whose extent is comparable to the diameter of the pin), a thermomechanically-affected region (TMAZ) and a heat-affected zone (HAZ). Frequently, the weld nugget appears to comprise equiaxed, fine, dynamically recrystallized grains whose size is substantially less than that in the parent material.

The objective of the present research was to develop a basic understanding of the evolution of microstructure in the dynamically recrystallized region and to relate it to the deformation process variables of strain, strain rate, and temperature. Such a correlation has not been attempted before perhaps because of the difficulty in quantifying the process variables. To overcome such difficulties, recent work [4] to measure and model the local temperature transients during FSW was utilized, and an approximate method was employed to estimate the strain and strain rate in the weld nugget.

Materials and Procedures

The material used in this investigation consisted of friction stir welded plates of an Al-Li-Cu alloy (Al-1.8 Li-2.7Cu-0.33Mg-0.33Mn-0.04 Zr-0.7Zn) which had been hot rolled, homogenized, solution heat treated, water quenched, and naturally aged prior to joining. The plate had a thickness of 7.6 mm and had been welded along the plate rolling direction using a 7.6 mm diameter pin. Optical metallography was performed to reveal the general microstructure of the weld and the base metal. Three-mm

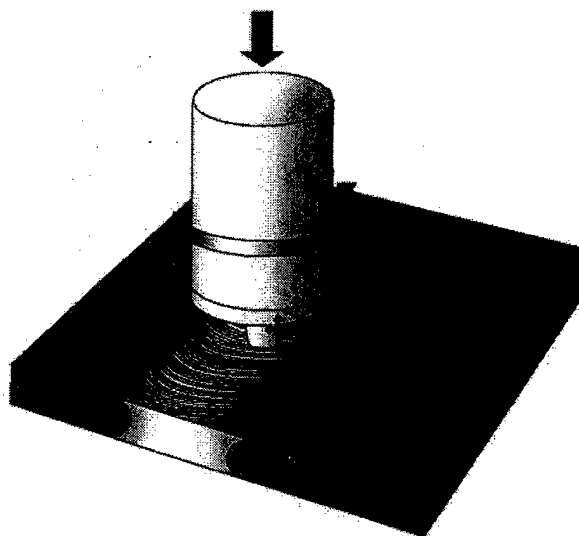


Figure 1. Schematic illustration of the friction stir welding process.

diameter foils were removed from the dynamically recrystallized region of the welds to obtain insight into the substructures that were generated during FSW. The foils were electropolished and observed under a transmission electron microscope (TEM) operated at 100 kV. Bright field (BF) micrographs and diffraction patterns were obtained to reveal grain size changes and detect the presence of precipitates and particles. The TEM observations were complemented by orientation imaging microscopy (OIM) measurements of misorientation angles and grain size. The OIM measurements were made using a standard electron backscatter pattern technique in a scanning electron microscope. For this purpose, a 50 μm step was used for the parent material and a 2 μm step was used for the welded (recrystallized) region.

Results

The principal results from this work consisted of optical, TEM, and OIM characterization of the starting (parent) material and the weld nugget/TMAZ regions of the FSW plates.

A. Parent Material Microstructure

The parent grains in the Al-Li base metal were highly elongated and pancake shaped (Figure 2a), mirroring the deformation imposed during rolling. These grains were several hundred micrometers long and approximately 75 μm thick. In addition, bright field TEM revealed that the elongated grains contained subgrains whose size was in the range of 2–10 μm (Figure 2b).

Orientation imaging microscopy (OIM) revealed similar grain-size data as well as measurements of misorientation angles. From the grain-size distribution (Figure 2c), the average grain area in the starting Al-Li alloy was approximately 6000 μm^2 , and the average grain diameter (assuming an equiaxed structure) was 87 μm . The misorientation distribution (Figure 2d) showed a large number of rotations less than 10°, and at approximately 60°.

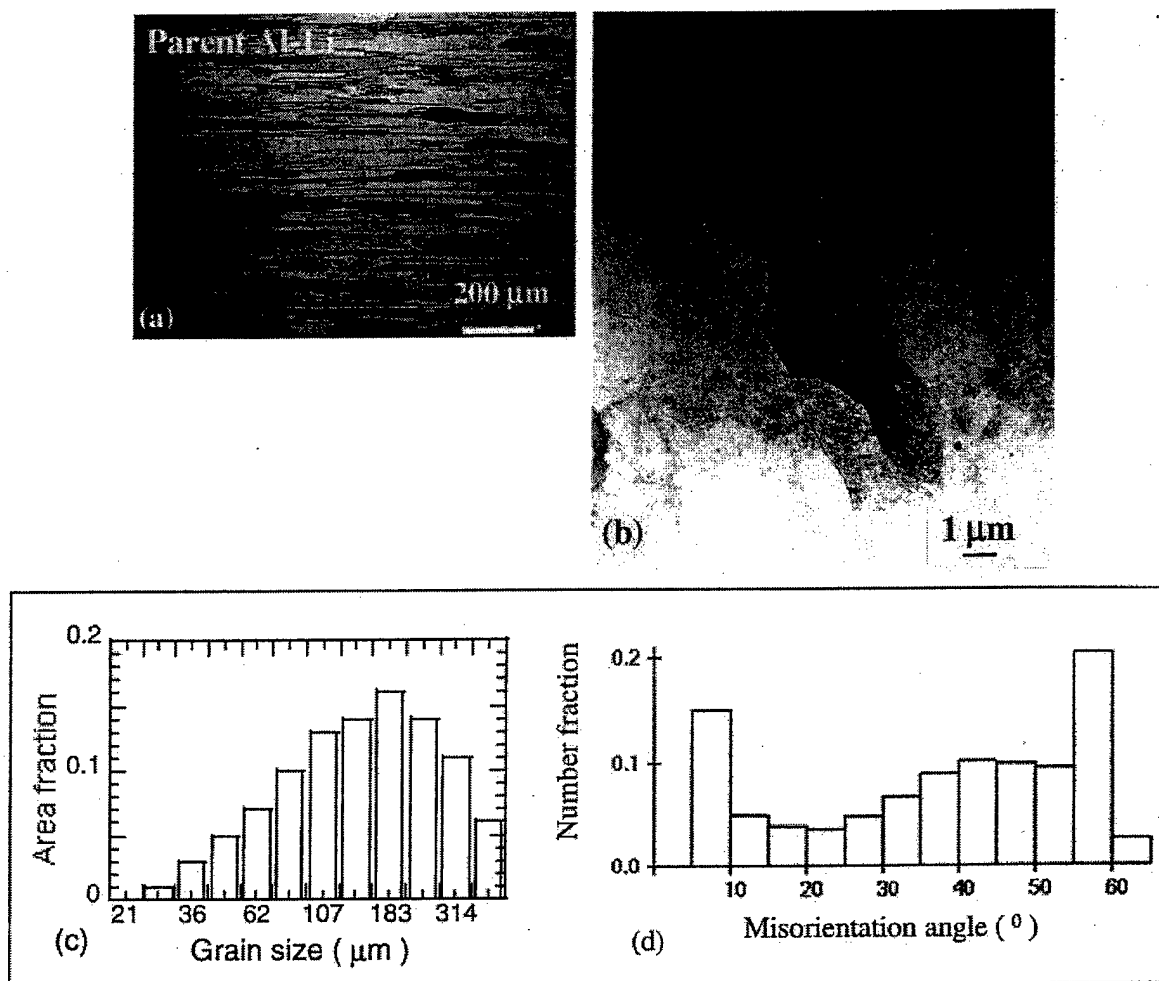


Figure 2. Starting Al-Li microstructures: (a) optical micrograph showing elongated-pancake grains; (b) BF TEM micrograph showing subgrains; (c) OIM grain size distribution and (d) OIM results for number fraction versus misorientation angle between grains.

B. Weld Zone Microstructure

Friction stir welding gave rise to noticeable microstructure changes in the Al-Li alloy. An optical micrograph revealed that deformation in the thermomechanically-affected zone (TMAZ) resulted in severe bending of the grain structure (Figure 3a). In contrast, the microstructure within the weld nugget in which dynamic recrystallization (DRX) occurred consisted of grains which were much smaller and equiaxed (Figure 3b) when compared to the severely-elongated and pancake-shaped parent metal microstructure (Figure 2a). Determined from OIM (Figure 4a), the grain-size distribution had an average area of $64 \mu\text{m}^2$ and average grain diameter of $9 \mu\text{m}$. Moreover, the grain-misorientation-angle-histogram for the DRX region (Figure 4b) showed a flatter distribution compared to the parent material. In particular, misorientations between 10 and 30 degrees were doubled, while the number between 30 and 60 degrees remained approximately constant.

Additional details about the DRX microstructure in the weld nugget of the Al-Li material were revealed in the TEM. For example, some grains were left with dislocation tangles at the boundaries

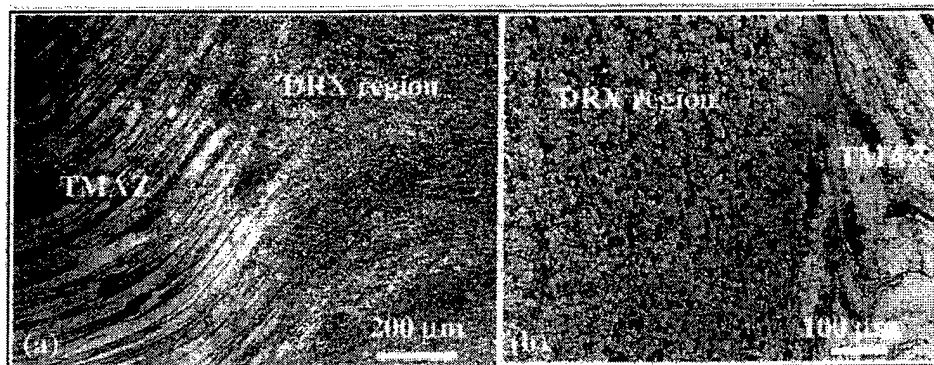


Figure 3. Optical micrographs of the Al-Li FSW region: (a) thermomechanically affected zone (TMAZ) and dynamically recrystallized (DRX) zone and (b) higher magnification photograph showing the DRX grains.

(Figure 5a) suggesting that recovery and/or recrystallization may not have been completed or was continuous in nature. Thus, these grains resemble cells rather than fully recovered grains. The majority of grains, however, were observed to have clean boundaries with no dislocation tangles at the boundaries (Figure 5b). Secondly, helical dislocation loops were observed in the grain interiors of a few grains. These loops are believed to have been generated during the thermal quench from the weld temperature to ambient temperature. Finally, the grain size developed in the dynamically recrystallized region was observed to be stable when heat treated to a commercially important aging temperature of 150°C for 65 hours.

Discussion

Microstructural Evolution Mechanisms

As-cast grain boundaries are pancaked, and subgrains are formed during the rolling of cast Al-Li ingot into a plate product form. For Al alloys containing coherent Al_3Zr dispersoids, it is difficult to break up the original cast grain boundaries unless special thermomechanical processing methods are used to recrystallize the cast material. In the Al-Li alloy used here, the original columnar grain boundaries of the cast material were retained in the parent metal even after a number of hot rolling passes.

With regard to the subgrains in the parent metal, lattice dislocations generated during a rolling operation can either attain a low energy dislocation structure (LEDs) configuration [5] or remain as homogeneously dispersed dislocations left in the interior of the grains. If sufficient dwell time is given

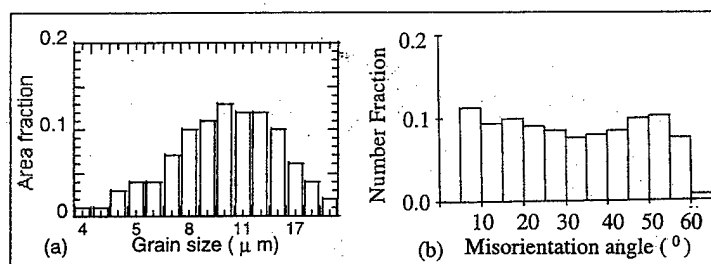


Figure 4. OIM data for the DRX region of an Al-Li FSW weld: (a) grain size distribution and (b) misorientation angle distribution.

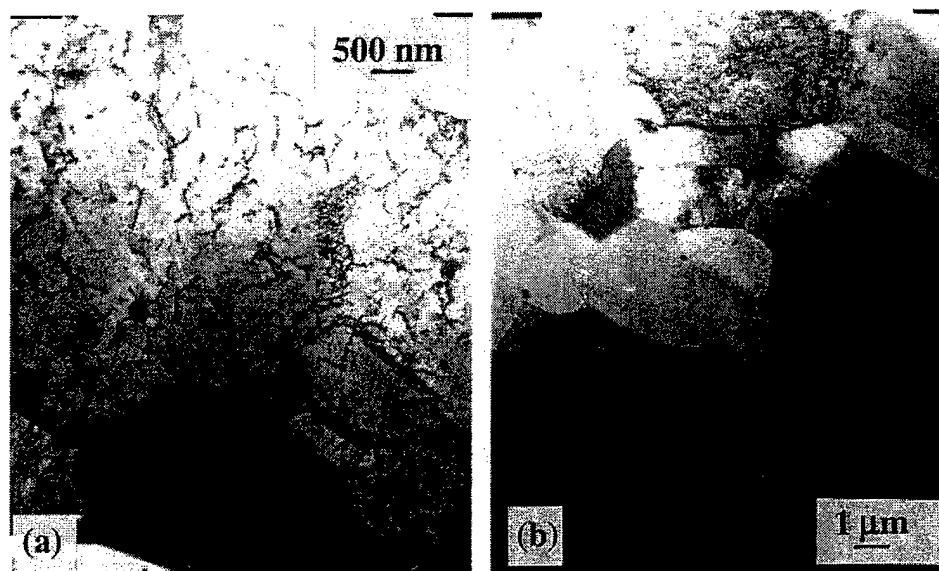


Figure 5. BF TEM micrographs showing the DRX microstructure: (a) cell-like substructure and (b) subgrains with dislocation-free boundaries.

between passes, the lattice dislocations achieve a well-defined low angle subgrain configuration (or a dislocation cell network). Subsequent rolling passes generate more lattice dislocations. The subgrain boundaries (or cell boundaries) absorb these dislocations [6]. Precipitation processes can also occur during hot rolling and/or the dwell time. In the case of the present Al-Li alloy, Al-Li-Cu rich precipitates [7] form and pin the subgrain boundaries (or cells). The dislocation density in the subgrain boundaries further increases with rolling passes, but the subgrain size remains fine due to the pinning action of the precipitates. The cell/subgrain interior is devoid of dislocations, and therefore a strain gradient exists across the cell/subgrain. To maintain plastic compatibility across boundaries, the subgrains rotate to larger angles. These processes can explain the misorientation angle histogram for the parent metal (Figure 2d).

During FSW, the original grain and subgrain boundaries appear to be replaced with fine, equiaxed recrystallized grains in the weld nugget. It is unlikely that dynamic recrystallization occurred via a 'discontinuous' process. The microstructural evidence (e.g., Figure 4,5) does not suggest that recrystallization nuclei formed and gross grain-boundary migration occurred as required by a discontinuous dynamic recrystallization mechanism. Rather, it appears that a 'continuous' dynamic recrystallization (CDRX) process, analogous to that which gives rise to subgrain formation during hot rolling and described above, was operative. The OIM measurements revealed that the magnitude of the misorientations increased noticeably during FSW relative to those in the parent (base) metal (Figure 2d, 5b). Thus, the 'grains' observed in the weld nugget are actually high-misorientation subgrains.

Several mechanisms of CDRX by which subgrains rotate and achieve a high misorientation have been proposed, [8,9]: Lattice rotation associated with slip [9], lattice rotation associated with boundary sliding, and subgrain growth. Two of these possibilities are readily eliminated as a controlling mechanism. Boundary sliding with grain rotation is a feature that is characteristic of superplasticity and is believed not to operate during high strain rate processes such as FSW. Subgrain growth may also be ruled out because many of the recrystallized grains formed in the DRX region are finer than the starting subgrain size. Hence, the process that appears to explain the present observations is the dislocation-glide-assisted-subgrain-rotation model. In this model, dislocation glide gives rise to a gradual relative rotation of adjacent subgrains.

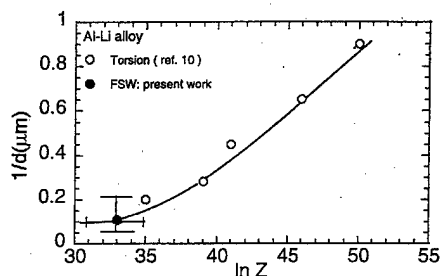


Figure 6. Dependence of inverse subgrain size on $\ln Z$ for Al-Li alloy deformed via hot torsion or FSW.

Recrystallized Grain Size

The grain/subgrain size developed in the weld nugget during FSW also suggests that recrystallization has occurred via a CDRX mechanism. This conclusion was reached by comparing the FSW grain size to that developed in Al-Li alloys processed via hot forging or torsion [10]. In these deformation modes, the subgrain size has been found to be a function of the Zener-Hollomon parameter $Z = \dot{\epsilon} \exp(Q/RT)$ in which $\dot{\epsilon}$, T denote the deformation strain rate and temperature, Q is the activation energy for the process, and T is temperature. Figure 6 shows the relation between d^{-1} and $\ln Z$ for an Al-Li alloy similar to the one used in the present program. A value of Q equal to 190 kJ/mol has been used to determine Z . To compare the observed grain size in the weld nugget to the data in Figure 6, Z , and thus $\dot{\epsilon}$ and T , must be determined. The strain rate $\dot{\epsilon}$ was estimated from measurements of shear strains versus position (of the sheared grains in the TMAZ), which were extrapolated to the weld zone. The deformation time was taken to be equal to the pin diameter divided by the traverse speed. The average effective strain rate was then calculated as the quotient of the shear strain and $\sqrt{3}$ times the deformation time. By this means, $\dot{\epsilon}$ was estimated to be 10 s^{-1} .

Previous measurements of the temperature profiles adjacent to the tool pin/shoulder have suggested that the temperature in the weld nugget during FSW is approximately 500°C . Because of uncertainties associated with thermocouple placement and direct temperature measurement, the former temperature estimates were supplemented in the presented work by TEM observations of the precipitates in the Al-Li weld nugget. These observations revealed a supersaturated solid solution. Thus, the solutionizing temperature (540°C) was used in calculating Z .

Using the strain rate of 10 s^{-1} , temperature of 540°C , and activation energy of $190 \text{ kJ/mol}^\circ\text{K}$ a value of $\ln Z = 31.0$ was calculated for the deformation in the FSW weld nugget. The values of d^{-1} and $\ln Z$ (with approximate scatter bands indicating uncertainty in the measurements and calculations) are plotted in Figure 6. The FSW datum falls on the trend line for the previous measurements on hot worked Al-Li samples, thus supporting the conclusion regarding the continuous dynamic recrystallization process during FSW.

Summary

Optical and TEM microstructures of friction stir welds of an Al-Li alloy were examined to establish the mechanism of the evolution of microstructure in the dynamically recrystallized (DRX) region of FSW welds. The average grain diameter in the DRX region was $9 \mu\text{m}$. Using orientation imaging microscopy, many of the grain boundary misorientations created in the DRX region were observed to be between 15 to 35° . Based on the observations, it was concluded that recrystallized grains in the DRX region form by a continuous dynamic recrystallization mechanism. Using reasonable estimates of the

strain rate and temperature in the FSW nugget, the dependence of the DRX grain size was found to have the same dependence on the Zener-Hollomon parameter as material deformed via conventional hot working process.

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